

What is claimed is:

1 1. A timing error estimation apparatus for multi-
2 carrier systems, comprising:

3 a timing offset compensator for receiving a current
4 symbol in a frequency domain after taking an N -
5 point Discrete Fourier Transform (DFT) and
6 compensating said current symbol for an effect of
7 timing offset with a timing offset prediction
8 value; and

9 a timing error estimator coupled to said timing offset
10 compensator to take a timing compensated version
11 of said current symbol on pilot subcarrier
12 locations, for calculating a timing error value
13 based on a function of a phase tracking value, a
14 channel response of each pilot subcarrier,
15 transmitted data on each pilot subcarrier, and
16 said timing compensated version of said current
17 symbol on said pilot subcarrier locations.

1 2. The apparatus as recited in claim 1 wherein said
2 timing error value of said current symbol, $\tau_{\epsilon,i}$, is defined
3 by:

4
$$\tau_{\epsilon,i} = \tau_{E,i} - \tau_{P,i}$$

5 where

6 subscript i denotes a symbol index,

7 $\tau_{E,i}$ is a measure of timing offset of symbol i ,

8 $\tau_{P,i}$ is said timing offset prediction value of symbol i ,

9 and

10 $\tau_{\epsilon,i}$ represents said timing error value of symbol i .

1 3. The apparatus as recited in claim 1 wherein said
 2 timing error estimator calculates said timing error value by
 3 the following function:

$$4 \quad \tau_{\epsilon,i} = -\frac{N}{2\pi} \frac{\text{Im}\left\{e^{-j\phi_{T,i}} \sum_{m=1}^{N_{SP}} p_m R'_{i,p_m} (H_{p_m} X_{i,p_m})^*\right\}}{\sum_{m=1}^{N_{SP}} p_m^2 |H_{p_m}|^2}$$

5 where

6 superscript * denotes complex conjugation,
 7 $\text{Im}\{\cdot\}$ denotes the imaginary part of a complex number,
 8 $\phi_{T,i}$ denotes said phase tracking value of symbol i ,
 9 N_{SP} is the number of said pilot subcarriers,
 10 p_m denotes a pilot subcarrier index, for $m=1, 2, \dots, N_{SP}$,
 11 H_{p_m} denotes said channel responses of pilot subcarrier
 12 p_m ,
 13 X_{i,p_m} denotes said transmitted data on pilot subcarrier
 14 p_m of symbol i ,
 15 R'_{i,p_m} denotes said timing compensated version of the i th
 16 symbol on pilot subcarrier location p_m , and
 17 $\tau_{\epsilon,i}$ denotes said timing error value of symbol i .

1 4. The apparatus as recited in claim 1 wherein said
 2 timing offset compensator is employed to compensate the i th
 3 symbol on pilot subcarrier location p_m using said timing
 4 offset prediction value of the i th symbol and provides as
 5 output said timing compensated version of the i th symbol on
 6 pilot subcarrier location p_m .

1 5. A timing tracking apparatus for multi-carrier
 2 systems, comprising:

3 a parameter table for storing a plurality of loop
4 parameters;
5 an *n*th-order tracking loop for computing a timing
6 offset prediction value for a next symbol based
7 on a timing error value of a current symbol, said
8 timing offset prediction value of said current
9 symbol and said loop parameters that are
10 retrieved from said parameter table for said
11 current symbol; and
12 a timing synchronizer for generating a shift amount of
13 a DFT window for said next symbol according to
14 said timing offset prediction value of said next
15 symbol, in which said DFT window shift amount is
16 equal to zero if said timing offset prediction
17 value of said next symbol is within a
18 predetermined range;
19 wherein said timing synchronizer applies said DFT
20 window shift amount to align the DFT window and
21 further starts an inhibit interval if said shift
22 amount is not equal to zero, and provides said
23 DFT window shift amount for further subtraction
24 from said timing offset prediction value upon
25 completion of said inhibit interval.

1 6. The apparatus as recited in claim 5 wherein said
2 timing synchronizer sets said DFT window shift amount to
3 zero for said next symbol during said inhibit interval,
4 except upon the start of said inhibit interval.

1 7. The apparatus as recited in claim 5 wherein said
2 *n*th-order tracking loop computes a timing offset tracking

3 value and a period offset tracking value for said current
4 symbol based on said loop parameters regarding said current
5 symbol, said period offset tracking value of a preceding
6 symbol, said timing offset prediction and said timing error
7 values of said current symbol, and yields said timing offset
8 prediction value for said next symbol by summing said timing
9 offset and said period offset tracking values of said
10 current symbol.

1 8. The apparatus as recited in claim 5 wherein said
2 *n*th-order tracking loop is a second-order tracking loop
3 modeled with a set of recursive equations, as follows:

$$\begin{aligned} \tau_{T,i} &= \tau_{P,i} + \mu_{\tau,i} \tau_{\epsilon,i} \\ \nu_{T,i} &= \nu_{T,i-1} + \mu_{\nu,i} \tau_{\epsilon,i} \end{aligned}$$

5 and

$$\tau_{P,i+1} = \tau_{T,i} + \nu_{T,i}$$

7 where

8 subscript *i* denotes a symbol index,
9 $\tau_{T,i}$ and $\nu_{T,i}$ denote a timing and period offset tracking
10 value of symbol *i*, respectively,
11 $\mu_{\tau,i}$ and $\mu_{\nu,i}$ denote said loop parameters of the *i*th
12 symbol for $\tau_{T,i}$ and $\nu_{T,i}$, respectively,
13 $\tau_{P,i}$ denotes said timing offset prediction value of the
14 *i*th symbol,
15 $\tau_{P,i+1}$ is said timing offset prediction value of symbol
16 *i*+1,
17 $\nu_{T,i-1}$ is said period offset tracking value of symbol *i*-1,
18 and $\tau_{\epsilon,i}$, said timing error value of the *i*th symbol, is given
19 by:
20 $\tau_{\epsilon,i} = \tau_{E,i} - \tau_{P,i}$

21 where $\tau_{E,i}$ is a measure of timing offset of the i th symbol.

1 9. The apparatus as recited in claim 8 wherein said
2 second-order tracking loop receives as input a frequency
3 offset estimate and calculates an initial value for said
4 period offset tracking value as follows:

$$5 \quad \nu_{T,i} = -N' \cdot \frac{\hat{f}_d}{f_c}, \quad i = -1$$

6 and

$$7 \quad N' = \frac{T'}{T_s}$$

8 where

9 \hat{f}_d denotes said frequency offset estimate,
10 f_c denotes a nominal carrier frequency,
11 T' denotes a symbol interval,
12 T_s denotes a sampling period,
13 $\nu_{T,i}$ denotes said period offset tracking value of symbol
14 i , and
15 $\nu_{T,-1}$ denotes said initial value for $\nu_{T,i}$.

1 10. A timing offset compensation apparatus for multi-
2 carrier systems, comprising:

3 a timing offset compensator for receiving a current
4 symbol in a frequency domain after taking an N -
5 point Discrete Fourier Transform (DFT) and
6 compensating said current symbol for an effect of
7 timing offset with a timing offset prediction
8 value;
9 a timing error estimator for taking a timing
10 compensated version of said current symbol on
11 pilot subcarrier locations and calculating a

12 timing error value for said current symbol based
13 on a function of a phase tracking value, a
14 channel response of each pilot subcarrier,
15 transmitted data on each pilot subcarrier, and
16 said timing compensated version of said current
17 symbol on said pilot subcarrier locations; and
18 a timing tracking unit for receiving said timing error
19 value of said current symbol to generate said
20 timing offset prediction value and a shift amount
21 of a DFT window for a next symbol.

1 11. The apparatus as recited in claim 10 wherein said
2 timing error value of said current symbol, $\tau_{\epsilon,i}$, is defined
3 by:

$$4 \quad \tau_{\epsilon,i} = \tau_{E,i} - \tau_{P,i}$$

5 where

6 subscript i denotes a symbol index,

7 $\tau_{E,i}$ is a measure of timing offset of symbol i ,

8 $\tau_{P,i}$ is said timing offset prediction value of symbol i ,

9 and

10 $\tau_{\epsilon,i}$ represents said timing error value of symbol i .

1 12. The apparatus as recited in claim 10 wherein said
2 timing error estimator calculates said timing error value by
3 the following function:

$$4 \quad \tau_{\epsilon,i} = -\frac{N}{2\pi} \frac{\text{Im} \left\{ e^{-j\phi_{T,i}} \sum_{m=1}^{N_{SP}} p_m R'_{i,p_m} (H_{p_m} X_{i,p_m})^* \right\}}{\sum_{m=1}^{N_{SP}} p_m^2 |H_{p_m}|^2}$$

5 where

6 superscript * denotes complex conjugation,

7 $\text{Im}\{\cdot\}$ denotes the imaginary part of a complex number,
8 $\phi_{T,i}$ denotes said phase tracking value of symbol i ,
9 N_{SP} is the number of said pilot subcarriers,
10 p_m denotes a pilot subcarrier index, for $m=1, 2, \dots, N_{SP}$,
11 H_{p_m} denotes said channel responses of pilot subcarrier
12 p_m ,
13 X_{i,p_m} denotes said transmitted data on pilot subcarrier
14 p_m of symbol i ,
15 R'_{i,p_m} denotes said timing compensated version of the i th
16 symbol on pilot subcarrier location p_m , and
17 $\tau_{\varepsilon,i}$ denotes said timing error value of symbol i .

1 13. The apparatus as recited in claim 10 wherein said
2 timing offset compensator is employed to compensate the i th
3 symbol using said timing offset prediction value of the i th
4 symbol and provides as output said timing compensated
5 version of the i th symbol, $R'_{i,k}$, where subscript k denotes a
6 subcarrier index.

1 14. The apparatus as recited in claim 10 wherein said
2 timing tracking unit comprises an n th-order tracking loop to
3 generate said timing offset prediction value for said next
4 symbol by computing a timing offset tracking value and a
5 period offset tracking value of said current symbol.

1 15. The apparatus as recited in claim 14 wherein said
2 timing tracking unit further comprises a timing synchronizer
3 to receive said timing offset prediction value of said next
4 symbol from said n th-order tracking loop, generate said DFT
5 window shift amount for said next symbol, and further start
6 an inhibit interval if said shift amount is not equal to

7 zero, in which said DFT window shift amount is applied to
8 align the DFT window and is provided for further subtraction
9 from said timing offset prediction value upon completion of
10 said inhibit interval.

1 16. The apparatus as recited in claim 10 wherein said
2 timing tracking unit comprises:

3 a parameter table for storing a plurality of loop
4 parameters;

5 an *n*th-order tracking loop for computing said timing
6 offset prediction value for said next symbol
7 based on said timing error value of said current
8 symbol, said timing offset prediction value of
9 said current symbol and said loop parameters that
10 are retrieved from said parameter table for said
11 current symbol; and

12 a timing synchronizer for generating said DFT window
13 shift amount for said next symbol according to
14 said timing offset prediction value of said next
15 symbol, in which said DFT window shift amount is
16 equal to zero if said timing offset prediction
17 value of said next symbol is within a
18 predetermined range;

19 wherein said timing synchronizer applies said DFT
20 window shift amount to align the DFT window and
21 further starts an inhibit interval if said shift
22 amount is not equal to zero, and provides said
23 DFT window shift amount for further subtraction
24 from said timing offset prediction value upon
25 completion of said inhibit interval.

1 17. The apparatus as recited in claim 16 wherein said
2 timing synchronizer sets said DFT window shift amount to
3 zero for said next symbol during said inhibit interval,
4 except upon the start of said inhibit interval.

1 18. The apparatus as recited in claim 16 wherein said
2 n th-order tracking loop is a second-order tracking loop
3 modeled with a set of recursive equations, as follows:

$$\begin{aligned} \tau_{T,i} &= \tau_{P,i} + \mu_{\tau,i} \tau_{\epsilon,i} \\ v_{T,i} &= v_{T,i-1} + \mu_{v,i} \tau_{\epsilon,i} \end{aligned}$$

5 and

$$\tau_{P,i+1} = \tau_{T,i} + v_{T,i}$$

7 where

8 subscript i denotes a symbol index,

9 $\tau_{T,i}$ and $v_{T,i}$ denote a timing and period offset tracking
10 value of symbol i , respectively,

11 $\mu_{\tau,i}$ and $\mu_{v,i}$ denote said loop parameters of the i th
12 symbol for $\tau_{T,i}$ and $v_{T,i}$, respectively,

13 $\tau_{P,i}$ denotes said timing offset prediction value of the
14 i th symbol,

15 $\tau_{P,i+1}$ is said timing offset prediction value of symbol
16 $i+1$,

17 $v_{T,i-1}$ is said period offset tracking value of symbol $i-1$,

18 and $\tau_{\epsilon,i}$, said timing error value of the i th symbol, is given
19 by:

$$\tau_{\epsilon,i} = \tau_{E,i} - \tau_{P,i}$$

21 where $\tau_{E,i}$ is a measure of timing offset of the i th symbol.

1 19. The apparatus as recited in claim 18 wherein said
2 second-order tracking loop receives as input a frequency

3 offset estimate and calculates an initial value for said
4 period offset tracking value as follows:

$$5 \quad v_{T,i} = -N' \cdot \frac{\hat{f}_d}{f_c}, \quad i = -1$$

6 and

$$7 \quad N' = \frac{T'}{T_s}$$

8 where

9 \hat{f}_d denotes said frequency offset estimate,
10 f_c denotes a nominal carrier frequency,
11 T' denotes a symbol interval,
12 T_s denotes a sampling period,
13 $v_{T,i}$ denotes said period offset tracking value of symbol
14 i , and
15 $v_{T,-1}$ denotes said initial value for $v_{T,i}$.

1 20. The apparatus as recited in claim 16 wherein said
2 timing tracking unit further comprises a flip-flop that
3 receives as input said timing offset prediction value of
4 said next symbol and provides as output said timing offset
5 prediction value for said current symbol.